PB87-196788

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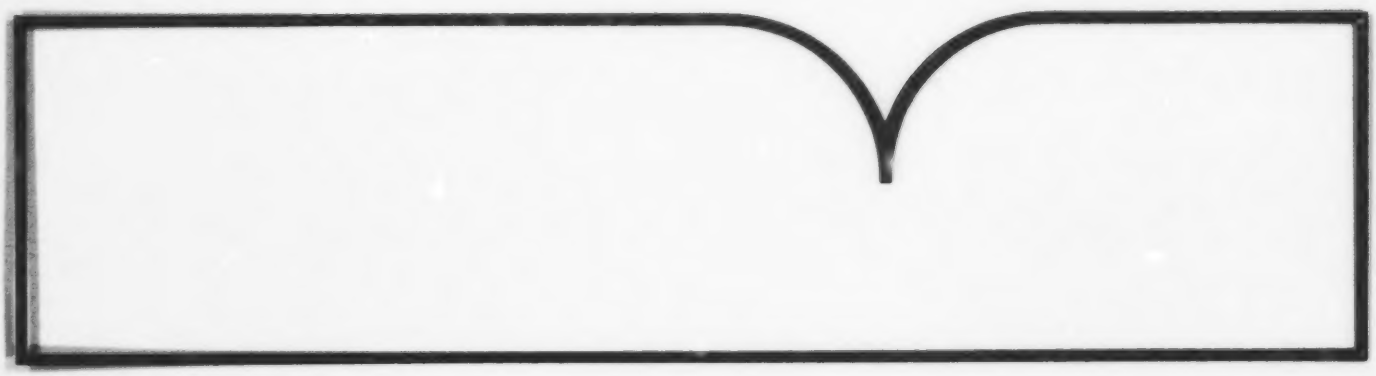
Acurex Corp., Research Triangle Park, NC

Prepared for

Environmental Protection Agency
Research Triangle Park, NC

May 87



U.S. Department of Commerce
National Technical Information Service

PB87-196788

EPA/600/D-87/169
May 1987

LOW NO_X, HIGH EFFICIENCY MULTISTAGED BURNER: FUEL OIL RESULTS

by

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EPA Contract 68-02-4213

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TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

1. REPORT NO.	2.	3. RECIPIENT'S ACCESSION NO.
EPA/600/D-87/169		
4. TITLE AND SUBTITLE Low NO_x, High Efficiency Multistaged Burner: Fuel Oil Results		5. REPORT DATE May 1987 6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) J. A. Mulholland (EPA) and R. K. Srivastava (Acurex)		8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS Acurex Corporation P. O. Box 13109 Research Triangle Park North Carolina 27709		10. PROGRAM ELEMENT NO. 11. CONTRACT/GRANT NO. 68-02-4213
12. SPONSORING AGENCY NAME AND ADDRESS EPA, Office of Research and Development Air and Energy Engineering Research Laboratory Research Triangle Park, NC 27711		13. TYPE OF REPORT AND PERIOD COVERED Journal Article; 3-5/87 14. SPONSORING AGENCY CODE EPA/600/13

15. SUPPLEMENTARY NOTES AEERL project officer is James A. Mulholland, Mail Drop 65, 919/541-7663.

16. ABSTRACT The paper discusses the fuel oil portion of an evaluation, utilizing a multistaged combustion burner designed for in-furnace NOx control and high combustion efficiency, for high nitrogen content fuel and waste incineration application in a 0.6 MW package boiler simulator. A low NOx precombustion chamber burner has been reduced in size by about a factor of two (from 600 to 250 ms first-stage residence time) and coupled with (1) air staging, resulting in a three-stage configuration, and (2) natural gas fuel staging, yielding up to four stoichiometric zones. Natural gas, doped with ammonia to yield a 5.8% fuel nitrogen content, and distillate fuel oil, doped with pyridine to yield a 2% fuel nitrogen content, were used to simulate high nitrogen content fuel/waste mixtures. The multistaged burner reduced NO emissions by 85% from emission levels from a conventional unstaged burner mounted on a commercial package boiler. A minimum NO emission level of 110 ppm was achieved in the fuel oil tests, from a level of 765 ppm for conventional firing. This is compared with a 160 ppm minimum NO level achieved in gaseous fuel tests, from an uncontrolled level of 1000 ppm. Boiler fuel staging, or reburning, appears to be superior to air staging for high combustion efficiency due to its minimal fuel-rich core and second flame front in the boiler.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Pollution Fuel Oil Nitrogen Oxides Combustion Incinerators Boilers Waste Disposal Simulators	Pollution Control Stationary Sources Multistaged Burners Package Boilers	13B 21D, 11H 14B 07B 21B 13A

18. DISTRIBUTION STATEMENT	19. SECURITY CLASS (This Report)	21. NO. OF PAGES
Release to Public	Unclassified	29
	20. SECURITY CLASS (This page) Unclassified	22. PRICE

EPA Form 2220-1 (9-73)

NOTICE

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Low NO_x, High Efficiency Multistaged Burner: Fuel Oil Results

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Abstract

A multistaged combustion burner designed for in-furnace NO_x control and high combustion efficiency is being evaluated for high nitrogen content fuel and waste incineration application in a 0.6 MW package boiler simulator. A low NO_x precombustion chamber burner has been reduced in size by approximately a factor of two (from 600 to 250 ms first-stage residence time) and coupled with (1) air staging, resulting in a three-stage configuration, and (2) natural gas fuel staging, yielding up to four stoichiometric zones. Natural gas, doped with ammonia to yield a 5.8 percent fuel nitrogen content, and distillate fuel oil, doped with pyridine to yield a 2 percent fuel nitrogen content, were used to simulate high nitrogen content fuel/waste mixtures. The multistaged burner reduced NO emissions by 85 percent from emission levels from a conventional unstaged burner mounted on a commercial package boiler. A minimum NO emission level of 110 ppm was achieved in the fuel oil tests, from a level of 765 ppm for conventional firing. This is compared with a 160 ppm minimum NO level achieved in gaseous fuel tests, from an uncontrolled level of 1000 ppm. Boiler fuel staging, or reburning, appears to be superior to air staging for high combustion efficiency due to its minimal fuel-rich core and second flame front in the boiler.

Introduction

The family of nitrogen oxide compounds, including nitric oxide (NO) and nitrogen dioxide (NO_2), is generally referred to as "NO_x." These NO_x species are formed during the combustion of coal, oil, and natural gas by the reduction and oxidation of molecular nitrogen (N_2) and nitrogen contained in the fuel. NO_2 is a poisonous gas that the United States Environmental Protection Agency (EPA) has designated as a criteria pollutant because of its harmful human health effects.[1] In addition, NO_x emissions are known to contribute to the formation of photochemical oxidants and are precursors, along with sulfur oxides (SO_x), of acid precipitation. Two more areas of concern are emerging regarding NO_x levels in the atmosphere. First, forest damage as a result of acid precipitation, reported to be extensive in the Federal Republic of Germany,[2] has been linked with increasing NO_x levels. Second, increasing levels of atmospheric nitrous oxide (N_2O) have been measured, levels that have been predicted to contribute to both a decline in the abundance of stratospheric ozone and an increase in climatic warming.[3] Studies of N_2O and NO concentrations in experimental flames and in flue gases have shown that a strong correlation exists between these two gases formed in combustion processes.

The EPA estimates that about 20 million tons (18,000 Gg) of NO_x are emitted annually from stationary and mobile sources in the United States. Unlike SO_x emissions, NO_x emissions have been increasing.[4] Coal- and oil-fired utility and industrial boilers account for over half of these NO_x emissions. Only 15 percent of the stationary NO_x sources are regulated by EPA's New Source Performance Standards (NSPS); the remainder must be addressed with retrofit technologies if significant NO_x emission reduction is to be realized. Another NO_x control problem is posed by the potential of incinerating high nitrogen content wastes in industrial boilers. While incineration of these materials

would not constitute a significant increase in the overall national NO_x emission level, individual plant emissions may be sufficient to result in a local NO_x problem and, thus, prevent on-site incineration from being permitted. With thermal destruction being an attractive alternative to landfill storage of wastes, there continues to be a need for developing high efficiency, low NO_x combustion technologies.

The vast majority of NO_x in stack combustion gas have been found to be NO. Much is known about the mechanisms of NO formation in flames, both from molecular nitrogen (source of thermal NO) and from fuel-bound nitrogen (source of fuel NO). Thermal NO can be reduced by decreasing peak flame temperatures. Fuel NO, not as strongly dependent on temperature, is very sensitive to reactant stoichiometry. Fuel-rich conditions promote N_2 formation over NO formation. Laboratory studies and field test data have established the importance of fuel NO to the total emission of NO_x from residual fuel oil and coal flames. Therefore, minimizing NO_x formation in flames typically involves controlling air and fuel mixing rates to create fuel-rich reducing zones and extracting heat to reduce final oxidation temperatures.

To avoid the need for costly post-combustion NO_x removal, several in-furnace NO_x control strategies have been developed and applied to boilers. These include reduced air preheat, load reduction, low excess air, flue gas recirculation, overfire air, deep air staging, fuel staging (or reburning), and various low-NO_x burner systems. While NO_x emissions can be reduced by 20 to 80 percent using these technologies, from uncontrolled levels exceeding 1000 ppm for some high nitrogen content coals, application of these combustion modifications can result in reductions in combustion efficiency and increases in sooting and slagging in the boiler. This problem is of particular concern in the boiler co-firing of fuels and wastes, where high waste destruction efficiencies

and minimal formation of other incomplete combustion products are of paramount importance. The purpose of this work is to investigate various multistaged combustion concepts for burning high nitrogen fuel/waste streams with low NO_x emissions and high combustion efficiency. Specifically, tests were designed to evaluate the use of a precombustion chamber burner, modified to reduce burner size, coupled with air or air/fuel staging. A NO_x emission of less than 0.2 lb (as NO_2)/10^6 Btu (or approximately 175 ppm NO_x, measured dry at zero percent O_2) for firing gaseous and liquid fuels doped with up to 5 percent nitrogen (by weight) was targetted.* (1 lb/10^6 Btu = 0.43 kg/GJ.) In this paper pilot-scale test results are presented on the performances of the proposed firing designs.

Before describing the experimental procedure and results, some background information is provided.

Precombustion Chamber Burner

The precombustion chamber burner is a staged combustion technology capable of achieving a NO_x emission of less than 0.1 lb (as NO_2)/10^6 Btu (or approximately 90 ppm NO_x), even with high nitrogen content fuel firing.[5] It consists of a primary air and fuel injection system, a large refractory wall precombustion chamber, and a secondary air injection section. Fuel and primary air are injected for rapid mixing into the nearly adiabatic precombustion chamber with a first-stage stoichiometry of between 0.6 and 0.8. A residence time between 0.6 and 1.0 s allows for maximum reduction and conversion of fuel nitrogen species to N_2 in the fuel-rich precombustion chamber. First-stage combustion gas products exit the burner through a convergent section which minimizes both radiative heat loss to the boiler and back-mixing of the secondary air. The transition section between the burner and boiler is water-cooled to reduce combustion gas temperatures before final air addition.

The precombustion chamber burner has been tested on a full-scale (16 MW_t)

crude-oil-fired steam generator used for thermally enhanced oil recovery (TEOR) in Kern County, CA.[6] A 30-day continuous monitoring test demonstrated the burner's ability to maintain a nominal NO_x emission of 70 ppm and a high combustion efficiency. During burner optimization testing, NO_x, CO, and smoke emissions were measured over a range of first-stage stoichiometries. These data indicate the sensitivity of NO_x emission to first-stage stoichiometry and the good hydrocarbon burnout characteristics of the burner. Earlier pilot-scale tests firing nitrogen-free fuels suggest that the minimum NO_x level of about 50 ppm can be attributed to second-stage thermal NO_x formation.

A test designed to demonstrate the potential for using this burner for nitrogenous waste incineration was performed at EPA's Air and Energy Engineering Research Laboratory. A pilot-scale (0.6 MW) precombustion chamber burner was used to incinerate a surrogate nitrogenous waste mixture of 9.1 percent (by volume) pyridine in fuel oil. A NO_x emission of less than 100 ppm was maintained, with greater than six nines (99.9999 percent) destruction of the pyridine being achieved. The relative NO_x emissions with and without pyridine addition indicate that less than 1 percent of the fuel nitrogen was converted to NO. This preliminary result sparked interest in utilizing the precombustion chamber burner for low NO_x, high efficiency combustion.

However, while the precombustion chamber burner has been demonstrated successfully in pilot-scale and field tests, its large size makes it impractical for most boiler retrofit applications. Reducing the burner size results in insufficient first-stage residence time to fully convert the fuel nitrogen to N_2; hence, higher NO_x emissions result. Further NO_x control can be achieved by further staging of the combustion process in the boiler.

Staged Combustion

The concept of staged combustion consists of injecting secondary air into

the boiler downstream of the primary combustion zone, which is characterized by substoichiometric levels of combustion air. This concept may be employed by utilizing overfire air ports, secondary air injectors, or burners-out-of-service. In application with a precombustion chamber burner, further air staging may extend the fuel-rich first stage from the burner into the boiler.

Reburning

Since 1982 EPA has carried out both in-house and extramural bench- and pilot-scale reburning tests. In-house experiments have focussed on natural gas and fuel oil reburning.[7-9] Significant results include quantifying the dependence of reburning effectiveness on primary flame NO_x level, reburn zone stoichiometry, and reburn fuel nitrogen content. Fifty percent NO_x reduction was possible with 15 to 20 percent of the fuel used for reburning. At low primary NO_x levels, however, a nitrogen-free reburning fuel (such as natural gas) must be used to achieve 50 percent reduction. Tests have shown that reburning is effective over a wide range of temperatures and with relatively short reburning zone residence times (0.2 to 0.4 s).

In application with a precombustion chamber burner, reburning would result in a four-stage combustion process. Because much of the primary fuel has been reduced prior to boiler entry, reburning might be applied from the front wall of the boiler. Such reburning application would simplify the boiler retrofit requirement by not requiring multiple boiler penetrations.

Experimental Methods

The goal of this study was to minimize NO_x formation, with an emission target of 175 ppm (dry, at zero percent O_2) or less, and maintain efficient incineration of surrogate fuel/waste mixtures with up to 5 percent fuel nitrogen by using a precombustion chamber burner reduced in size by about half.

The facility, shown schematically in Figure 1, consists of a vertical precombustion chamber low-NO_x burner and a horizontal package boiler simulator. The precombustion chamber consists of a primary fuel and air injection module, several 0.25 m long spool modules with 0.51 m internal diameter, and a convergent elbow module. These burner modules have a thick refractory wall lining to minimize heat loss and, thus, maintain high temperatures that promote conversion of fuel nitrogen to N_2 under fuel-rich stoichiometries. To achieve rapid mixing in the precombustion chamber, the primary fuel is injected through a divergent nozzle, and the primary air, which is not preheated, is passed through fixed swirl vanes. The convergent elbow module minimizes back-mixing of combustion gas and radiation loss to the boiler. A water-cooled transition module, 0.25 m in internal diameter, cools the combustion gas before secondary air addition to minimize thermal NO generation. Primary fuel nitrogen is simulated by doping ammonia into natural gas or pyridine into distillate fuel oil. Gaseous fuel results have been previously reported;[10] fuel oil results are presented in this paper.

The pilot-scale boiler simulator is rated at 0.9 MW thermal input. The boiler's radiant section is horizontal, 0.6 m in diameter, 3.0 m long, and cooled with Dowtherm G® heat transfer fluid. Combustion gas exits the boiler through a vertical stack. The boiler's front face has eight axial ports for addition of staged air.

For these tests, a burner length of 1.8 m, corresponding to a nominal residence time of 250 ms, was used. A 5 cm diameter port was available for staging fuel into the burner. Two of the eight axial air ports on the package boiler simulator front face were modified to provide ports for staging fuel into the boiler at an angle of 45 degrees. This design allows for reburning application from the boiler front face, with aerodynamic separation of the

fuel-lean and fuel-rich zones in the boiler. The end plate of the boiler has been modified to allow the insertion of a water-cooled boom injector for deep staging of air into the boiler.

The experimental facility is designed for independent control and measurement of each fuel, fuel dopant, and air stream. Stack gas speciation is measured by a continuous emissions monitoring system. NO and NO_x are measured by chemiluminescence. Reported in this paper are NO measurements only, measured on a dry basis and corrected to zero percent O_2. Spot-check measurements of NO_x indicated that NO emissions accounted for over 95 percent of the exhaust NO_x emissions in these tests.

A North American (N.A.) Scotch-type package boiler was used to provide conventional burner results to be compared with the multistaged burner results. This boiler is a three-pass unit with a continuous service rating of 0.3 kg of steam per second (2400 lb/hr). Its size and thermal characteristics are nearly identical to those of the package boiler simulator.[7,8]

Evaluated were burner baseline performance and burner operation with various air staged and fuel staged NO_x controls. The parameters affecting the NO_x emissions from the facility with unstaged controls are fuel nitrogen content, combustion gas residence time in the prechamber, first-stage stoichiometry,

and exhaust stoichiometry. The residence time of combustion gas in the burner depends on precombustion chamber length, load, and stoichiometry. The nominal load was 0.6 MW. The exhaust stoichiometry was kept at a nominal value of 15 percent excess air, as per commercial boiler practice. Nominal fuel nitrogen content for the fuel oil/pyridine mixture was 2 percent by weight; for the natural gas/ammonia fuel, nominal fuel nitrogen content was 5.8 percent. First-stage stoichiometry was optimized for each NO_x control application tested.

Burner Baseline Performance

During low NO_x burner characterization tests, the effects of first-stage stoichiometry, excess air, load, and fuel nitrogen content on NO emissions were studied.

Burner Stoichiometry Variation

First-stage stoichiometry was varied by changing the primary air flow. Secondary radial air was adjusted to maintain 15 percent excess air. The results are plotted in Figure 2. The curves indicate a strong sensitivity of stack NO to changes in burner stoichiometry. For the gas tests, a minimum NO emission of 315 ppm occurred at a burner stoichiometry of about 0.78; for the oil tests, a minimum of 190 ppm occurred at 0.65. Thus, additional combustion modifications are necessary to meet the program goal of less than 175 ppm.

The shift in optimum burner stoichiometry suggests a variation in the thermal environment in the precombustion chamber. In Figure 3, burner temperatures are shown, measured by suction pyrometry. Radiation and conduction errors are estimated to be less than 30 °C. The burner temperatures were found to be higher for the oil tests; thus, the shift in optimum stoichiometry.[5]

In tests on the North American boiler, a NO emission of 1000 ppm resulted when firing the 5.8 percent nitrogen gas fuel at 15 percent excess air. A NO emission of 765 ppm resulted when firing the 2 percent nitrogen oil mixture at 15 percent excess air. Thus, the low NO_x burner reduced NO emissions by 68 percent for the gas fuel and by 75 percent for the oil mixture.

Excess Air Variation

The effect of excess air variation on stack NO is shown in Figure 4. Excess air had a much stronger effect in the conventional North American burner tests than in the low NO_x burner tests, as expected. While reducing excess air did provide some NO reduction with the low NO_x burner, maintaining an exhaust excess air level of 15 percent is important for achieving high combustion efficiency.

Load Variation

The effect of load reduction on stack NO is shown in Figure 5. As load was decreased from a nominal condition of 0.6 MW to 65 percent of nominal, the stack NO concentration dropped by 20 to 25 percent in the low NO_x burner tests. With a conventional burner, NO emissions are reduced only slightly with burner derating, due to decreased air/fuel mixing intensity. However, with the low NO_x burner, the effect is much greater because load reduction corresponds to an increase in first-stage residence time and, thus, a decrease in NO emission. Reducing load by 35 percent increased burner residence time from 250 to 385 ms. However, boiler steam requirements make load reduction an impractical means of NO_x control.

Fuel Nitrogen Variation

The effect of fuel nitrogen variation is shown in Figure 6. Exhaust NO level increased with increasing fuel nitrogen content in the fuel/waste stream, as expected, with a much greater sensitivity observed in the conventional North American burner tests. These results demonstrate the precombustion chamber burner's ability to reduce fuel nitrogen to molecular nitrogen, even with its reduced size (250 ms). The full size (600 to 800 ms) precombustion chamber burner produces NO emissions even less sensitive to fuel nitrogen content.[5]

Air Staged NO_x Controls

During air staged NO_x control tests, the effect of moving the location of secondary air addition, from the radial ports in the transition section to the axial and deep staged ports in the boiler, was examined. The secondary air was distributed between radial and axial locations in one series of staging tests, and between radial and deep staged ports (located 132 cm from the boiler front face) in a second series of tests. This created a three-stage combustion process: a fuel-rich burner zone, a less fuel-rich (SR_2) zone after radial secondary air injection in the transition section, and a fuel-lean burnout zone after final air addition. A water-cooled boom, aligned with the centerline axis of the boiler, was used to supply the deep staged air.

Fuel oil/pyridine test results for the two cases of secondary air staging in the boiler are given in Table I. The axial air staging resulted in a drop in minimum NO concentration from 190 ppm with no staging to 150 ppm with 100 percent of the secondary combustion air moved from the radial injectors to the axial injectors. The reduced NO levels for air staging were due to lower combustion gas temperatures and delayed mixing of the secondary air and combustion gas. Hence, less thermal NO was generated and less fuel nitrogen species fragments were oxidized with axial air addition into the boiler than with radial addition into the transition section. Similarly, lower temperatures in the boiler at the deep staged air location and longer fuel-rich zone residence time resulted in a lower NO emission when the secondary air was deep staged. With all of the secondary air being added from the deep staged location, the minimum NO level was 130 ppm.

From the test results just described, deep staging of secondary air is shown to be an effective means of minimizing NO emissions. However, such staging may lead to burnout problems, which are of great concern when co-firing

waste. Extending the fuel-rich zone from the precombustion chamber into the boiler exposes the reducing combustion gases to cool boiler walls, which may result in slagging and/or sooting. Further, the lower combustion gas temperatures in the boiler slow the fuel-rich nitrogen kinetics.

Fuel Staged NO_x Controls

During fuel staged NO_x control tests, the effect of diverting part of primary fuel to staged locations in the burner and boiler was studied. The staged fuel was natural gas, with no ammonia dopant. In the case of fuel staging in the burner, the secondary natural gas was added, using a water-cooled injector, down the centerline axis of the boiler; secondary air was added axially into the boiler to allow sufficient fuel-rich zone residence time. In the case of fuel staging in the boiler, the secondary natural gas was added at an angle of 45 degrees, using water-cooled injectors, from two ports in the boiler front face. Secondary air to complete primary fuel combustion was added radially into the transition section, while burnout air for secondary fuel combustion was added axially near the boiler wall, using six axial ports on the boiler front face.

Burner Fuel Staging

Holding total load constant, fuel was diverted from the primary fuel injector to a secondary injector near the precombustion chamber exit (see Figure 1), thus creating two stoichiometric zones in the burner in addition to the burnout zone in the boiler. The staged fuel (undoped natural gas) provides a burst of hydrocarbon radicals that accelerates the reduction of primary fuel nitrogen to N_2 prior to secondary air injection. Secondary air was injected through the axial injectors. Two effects contribute to a decrease in NO emissions with fuel staging: (1) fuel nitrogen reduction mechanisms are accelerated

due to increased radical concentrations, and (2) combustion gases from the high nitrogen content primary fuel are diluted by the combustion gases from the nitrogen-free secondary fuel.

Fuel oil/pyridine results are given in Table I. At an initial burner stoichiometry of 0.65, with 35 percent of the fuel staged, the exhaust NO levels decreased to 110 ppm, from 150 ppm with no fuel staging (and axial secondary air addition). The table also shows that the initial burner stoichiometry can be made much less fuel rich (0.88), with a penalty in NO emission (205 ppm). This may be an attractive mode of operation for maximum incineration of the primary fuel/waste stream.

Boiler Fuel Staging

As in the tests just described, total boiler load was held constant while fuel was diverted from the primary fuel injector to two secondary injectors. In this case, the staged fuel (undoped natural gas) was injected into the boiler downstream of the secondary radial air addition. Thus, a four-stage combustion process was established, consisting of a fuel-rich burner zone and three boiler zones characteristic of reburning (i.e, fuel-lean, fuel-rich, fuel-lean). The stoichiometry in the third stage (SR_3, the fuel-rich reburning zone in the boiler) is critical in this NO_x control process. As already described, all of the staged air and fuel flows were injected from the front face of the boiler at various angles, resulting in the three boiler stoichiometric zones.

Fuel oil/pyridine results are given in Table I. NO emission decreased due to both primary NO destruction and primary combustion gas dilution. Two second-stage stoichiometries (SR_2) were established: 1.1 and 1.0. With 35 percent fuel staging, the exhaust NO levels were reduced to 120 ppm (from 190 ppm) at a SR_2 of 1.1 (and a SR_3 of 0.76) and to 110 ppm at a SR_2 of 1.0 (and a SR_3

of 0.69). Due to less distinct stoichiometric zones than typically established in reburning application, the NO reduction by fuel staging was not quite as great as that obtained when the staged fuel was injected farther downstream of the fuel-lean primary combustion zone.[7,8] However, the configuration used in these tests requires no boiler penetrations. In addition, complete destruction of the primary fuel/waste stream appears to be ensured by providing all of the required primary combustion air prior to entry into the boiler, and then passing the primary combustion gases through a secondary flame.

Table I. Summary of fuel oil/pyridine results.

Control Modification	Amount	NO, ppm (percent reduction)
Burner Baseline		
-N.A. Burner	------	765
-Low NO_x Burner	250 ms	190 (75)
Burner Characterization		
-Excess Air	5 %	175 (77)
-Load	65 %	140 (82)
-Fuel Nitrogen	1 %	150 (80)
Air Staging		
-Axial	100 %	150 (80)
-Deep	100 %	130 (83)
Fuel Staging		
-Burner	35 %	
-SR_1 = 0.65/0.45		110 (86)
-SR_1 = 0.88/0.61		205 (73)
-Boiler	35 %	
-SR_2 = 1.1		120 (84)
-SR_2 = 1.0		110 (86)

Discussion and Conclusions

Table I summarizes results from the various combustion modification schemes for the reduction of NO in the oil tests. These results were obtained at

optimal first-stage stoichiometries. From the table it can be seen that deep air staging and fuel staging in the boiler are most effective in minimizing NO emission, resulting in an overall NO reduction of about 85 percent. However, deep air staging not only presents problems of hardware modification due to boiler penetrations, but also may lead to inefficient combustion. On the other hand, the boiler fuel staging hardware modifications used in this study were designed with retrofit feasibility and efficient combustion in mind. In the boiler fuel staging tests described here, all of the secondary combustion air necessary for primary fuel burnout was introduced with rapid mixing at high temperatures in the water-cooled transition section between the burner and boiler. Furthermore, staged fuel and air from the front face of the boiler provided a secondary flame for increased primary fuel/waste destruction, similar to incinerator afterburners. However, fuel staging does result in more complicated operating procedures, particularly in following load changes.

Some mention should be made of the limitations of these results. First, little information has been collected to date on surrogate fuel/waste burnout. Burning gaseous and volatile oil mixtures allows for well-controlled parametric testing for NO emission evaluation, but does not provide for good burnout simulation. Also, first-stage fuel nitrogen conversion to molecular nitrogen is expected to be less for less volatile fuels. Therefore, NO emissions would tend to be lower for gas and volatile oil firing than for the firing of heavier fuels and wastes that require increased first-stage residence times for vaporization and/or pyrolysis.

Another limitation of this study is that the results are applicable only in the range of temperatures characteristic of the firetube package boiler. Temperatures in the package boiler simulator ranged from 1700 K at the boiler entry to 1250 K at the boiler exit. To avoid high thermal NO formation in the

primary combustion gas burnout, sufficient heat must be extracted in the transition section to lower the combustion gas temperatures from nearly adiabatic flame temperatures leaving the burner to less than 1800 K.

Finally, it should be noted that the low NO emissions from the fuel staging tests are achieved largely by dilution of the primary combustion gases with secondary flame gases, which do not have a fuel nitrogen input. Actual molar destruction of NO is small in these tests. However, this dilution is coupled with the NO formation and destruction processes and should not be discounted. From the standpoint of NO minimization and fuel/waste destruction maximization, overall emissions per unit mass of input should be considered. From this perspective, fuel staging in combination with the shortened precombustion chamber burner appears to be the most attractive combustion modification for high nitrogen content fuel/waste firing in boilers.

Acknowledgment

This work was funded by EPA's Air and Energy Engineering Research Laboratory at Research Triangle Park, North Carolina. The authors wish to express their appreciation for the support provided by Charles Pendergraph and Darryl Williams of Acurex Corporation.

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7. Mulholland, J.A., and Lanier, W.S., "Application of Reburning for NO_x Control to a Firetube Package Boiler," Journal of Engineering for Gas Turbines and Power, Vol. 107, No. 3, ASME, July 1985, pp. 739-743.

8. Mulholland, J.A., and Hall, R.E., "Fuel Oil Reburning Application for NO_x Control to Firetube Package Boilers," Journal of Engineering for Gas Turbines and Power, Vol. 109, No. 2, ASME, April 1987, pp. 207-214.

9. Lanier, W.S., Mulholland, J.A., and Beard, J.T., "Reburning Thermal and Chemical Processes in a Two-Dimensional Pilot-Scale System," Twenty-first Symposium (International) on Combustion, The Combustion Institute, 1986, in press.

10. Srivastava, R.K., and Mulholland, J.A., "Low NO_x, High Efficiency Multistaged Burner: Gaseous Fuel Results," Environmental Progress, in press.

* The current NSPS for large industrial boilers firing high nitrogen heavy fuel oil is 0.4 lb (as NO_2)/10^6 Btu. This standard is under review.

FIGURE CAPTIONS

Figure 1. Pilot-scale combustion research facility. The package boiler simulator has been fitted with a precombustion chamber burner and air and fuel staging ports.

Figure 2. Effect of burner stoichiometry. Shown are results from tests firing a 5.8 percent nitrogen gas fuel and a 2 percent nitrogen distillate fuel oil/pyridine mixture.

Figure 3. Burner temperatures. Shown are measurements firing the low NO_x burner on gas and oil fuels. The dashed line represents the adiabatic flame temperature of methane in air at 1 atm.

Figure 4. Excess air variation results. Shown are 5.8 percent nitrogen gas and 2 percent nitrogen oil results. The dashed lines represent results from the North American (N.A.) boiler tests.

Figure 5. Load variation results. Shown are results with a 5.8 percent nitrogen gas fuel and a 2 percent nitrogen oil mixture.

Figure 6. Fuel nitrogen variation results. Shown are results from firing a 5.8 percent nitrogen gas fuel and a 2 percent nitrogen oil mixture. The dashed lines represent data from the North American (N.A.) boiler tests.

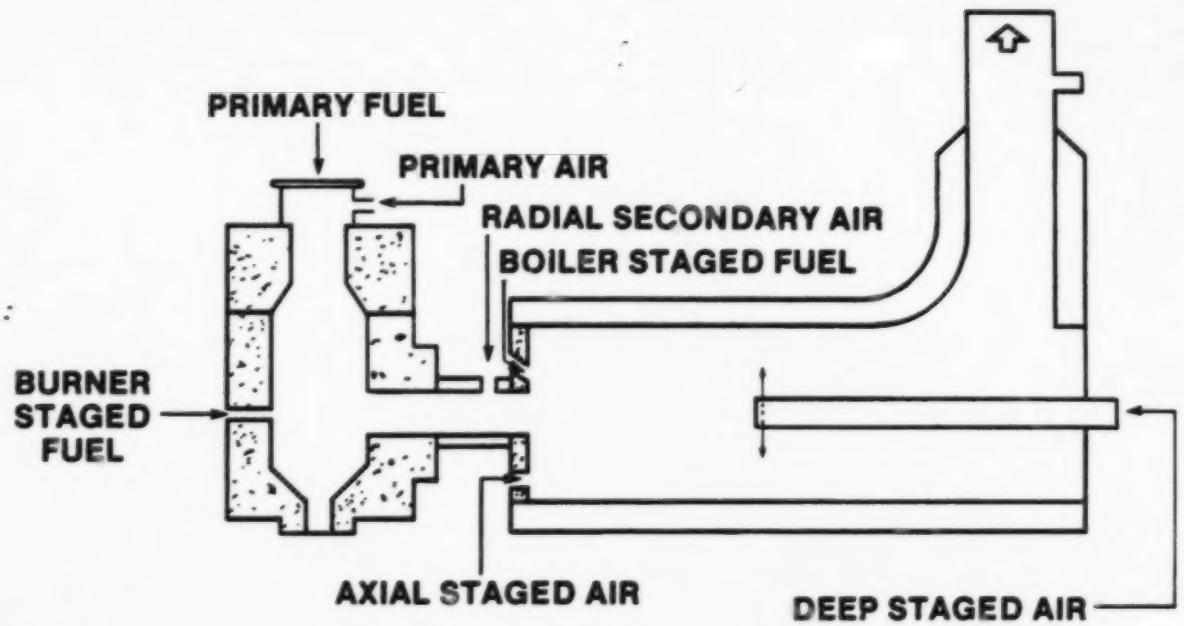
PRIMARY FUEL
PRIMARY AIR
RADIAL SECONDARY AIR
BOILER STAGED FUEL
BURNER STAGED FUEL
AXIAL STAGED AIR
DEEP STAGED AIR

FIGURE 1

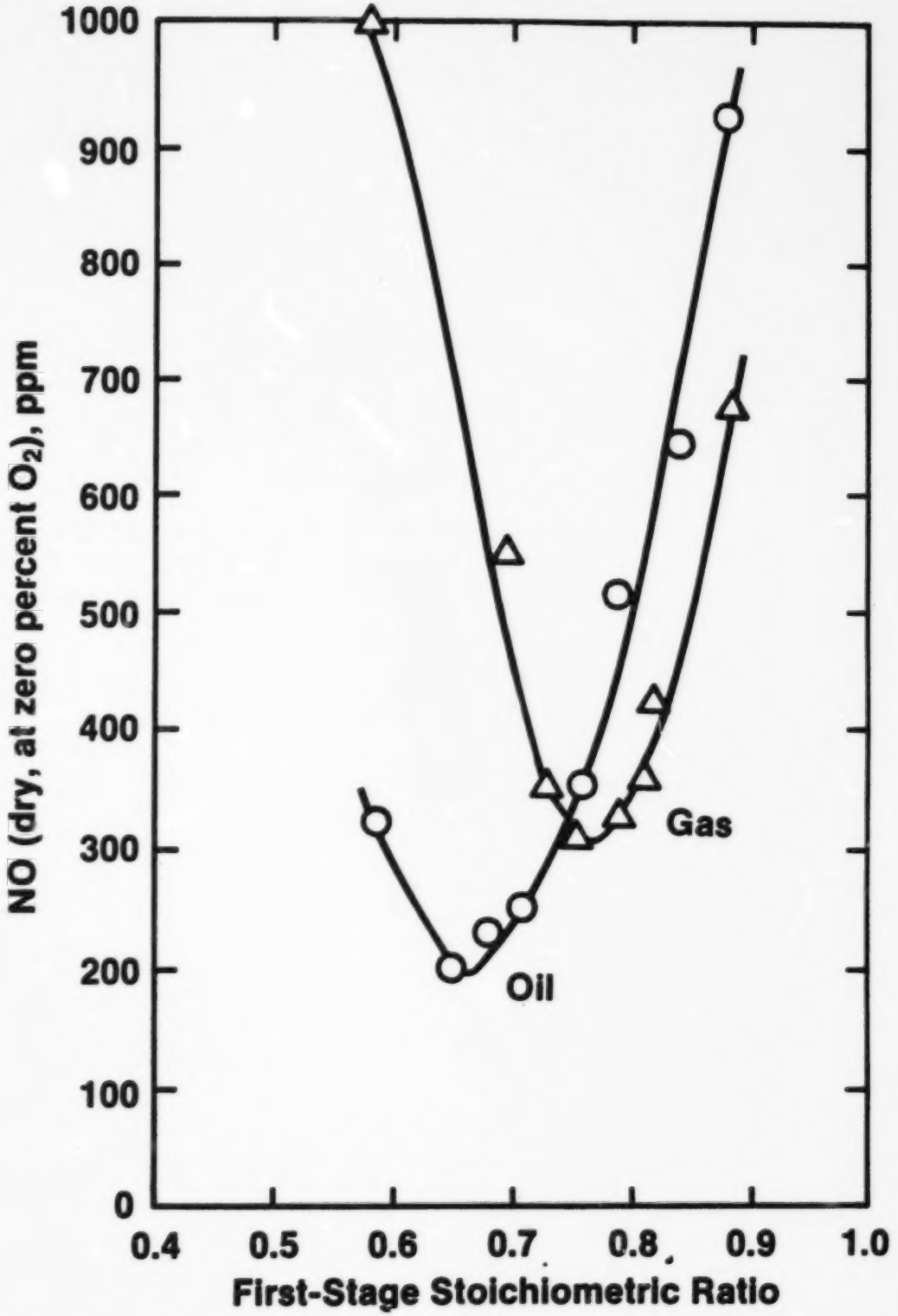
1000
900
800
700
600
500
400
300
200
100
0
NO (dry, at zero percent O_2), ppm
0.4
0.5
0.6
0.7
0.8
0.9
1.0
First-Stage Stoichiometric Ratio
Gas
Oil

FIGURE 2

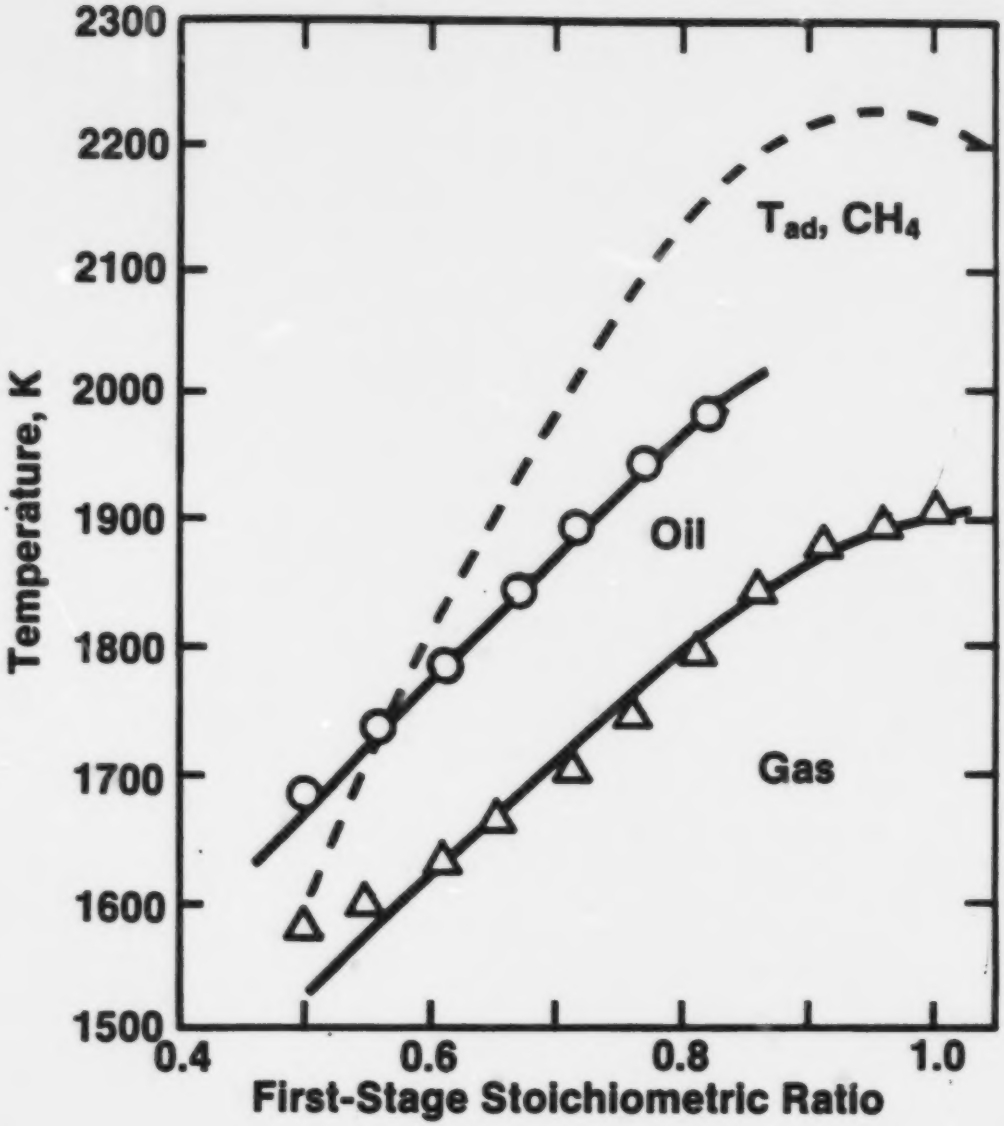
2300
2200
2100
2000
1900
1800
1700
1600
1500
Temperature, K
0.4
0.6
0.8
1.0
First-Stage Stoichiometric Ratio
T_{ad}, CH_4
Oil
Gas

FIGURE 3

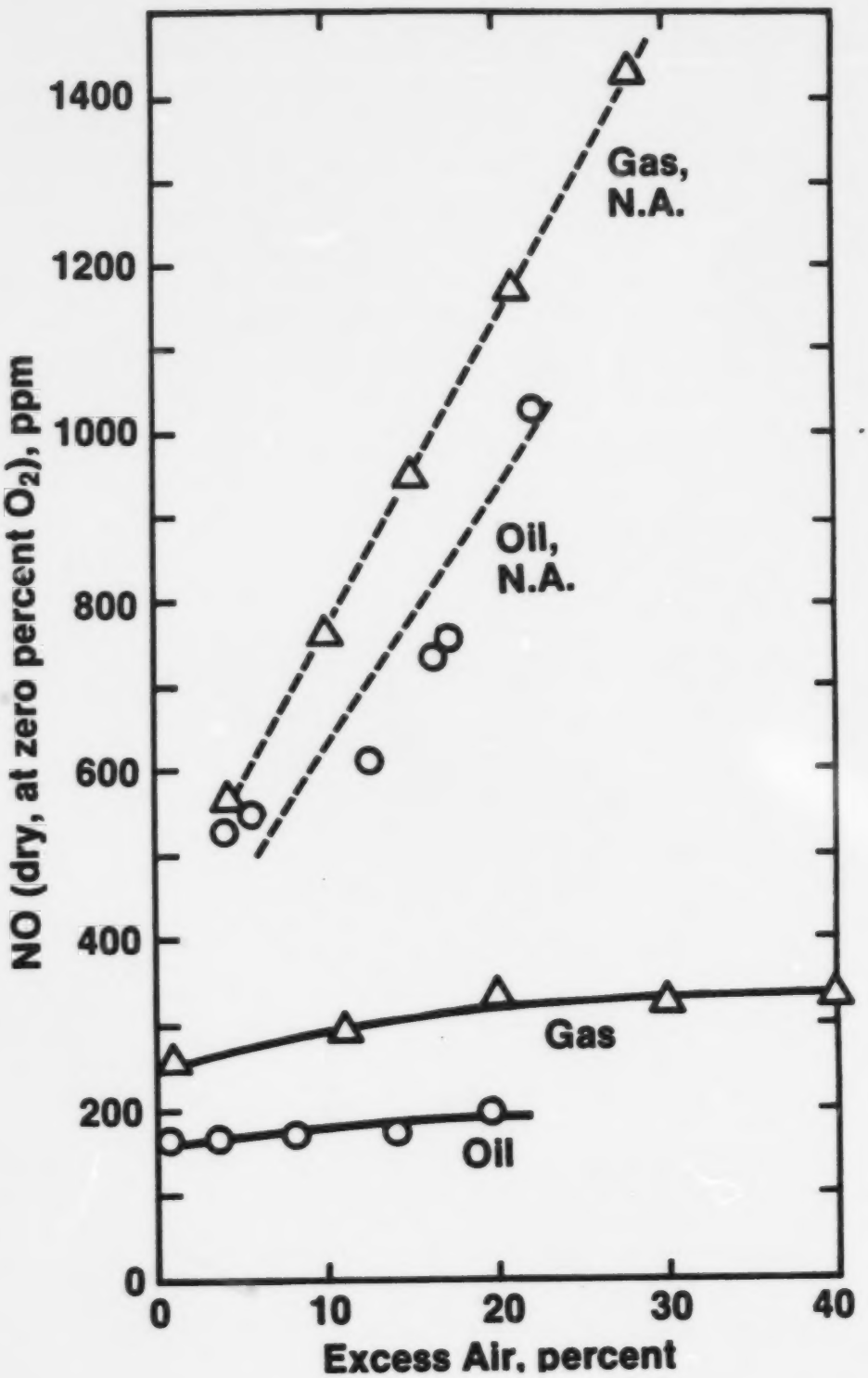
1400
1200
1000
800
600
400
200
0
NO (dry, at zero percent O_2), ppm
Gas, N.A.
Oil, N.A.
Gas
Oil
0
10
20
30
40
Excess Air, percent

FIGURE 4

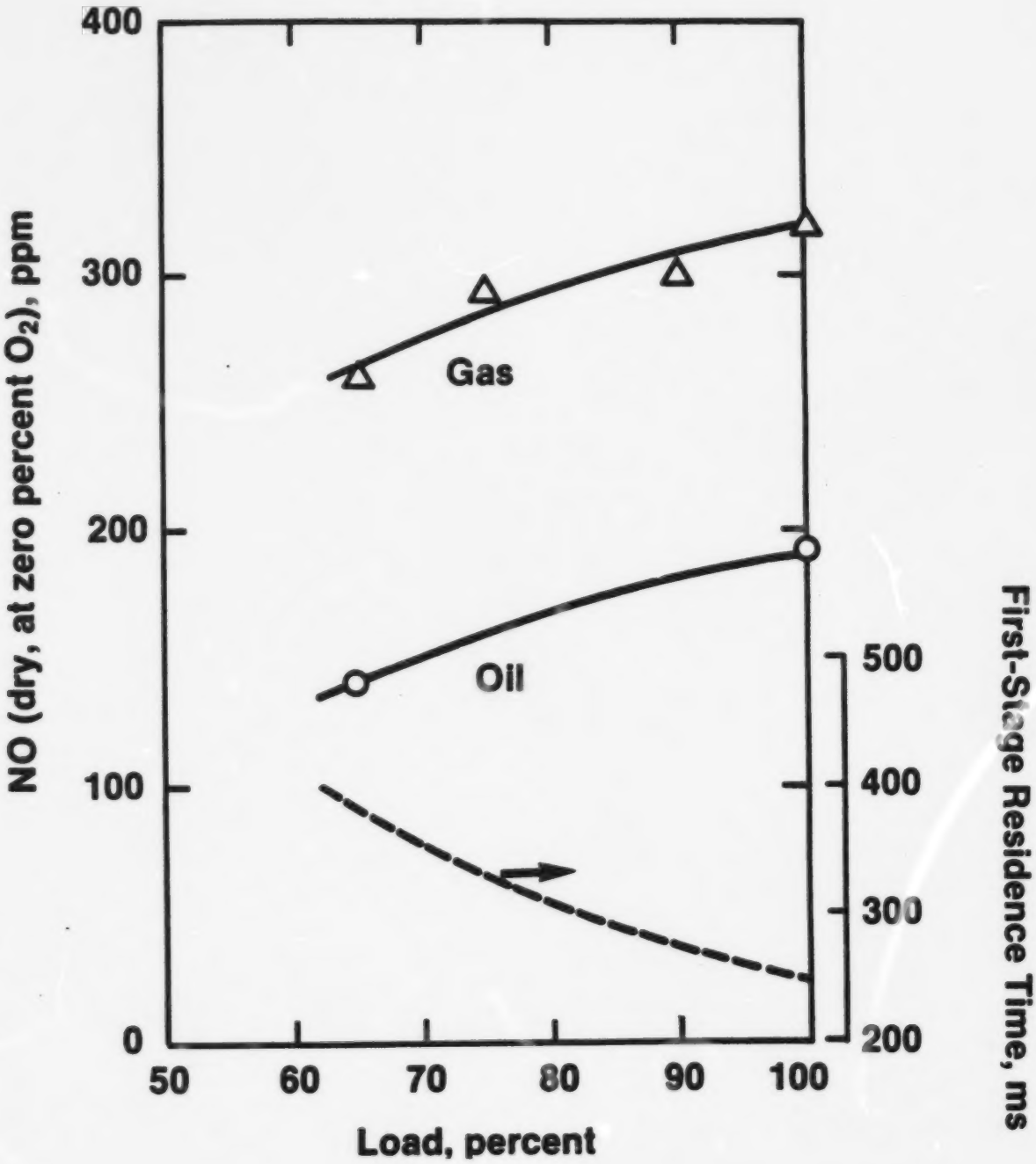
400
300
200
100
0
NO (dry, at zero percent O_2), ppm
Gas
Oil
500
400
300
200
First-Stage Residence Time, ms
50
60
70
80
90
100
Load, percent

FIGURE 5

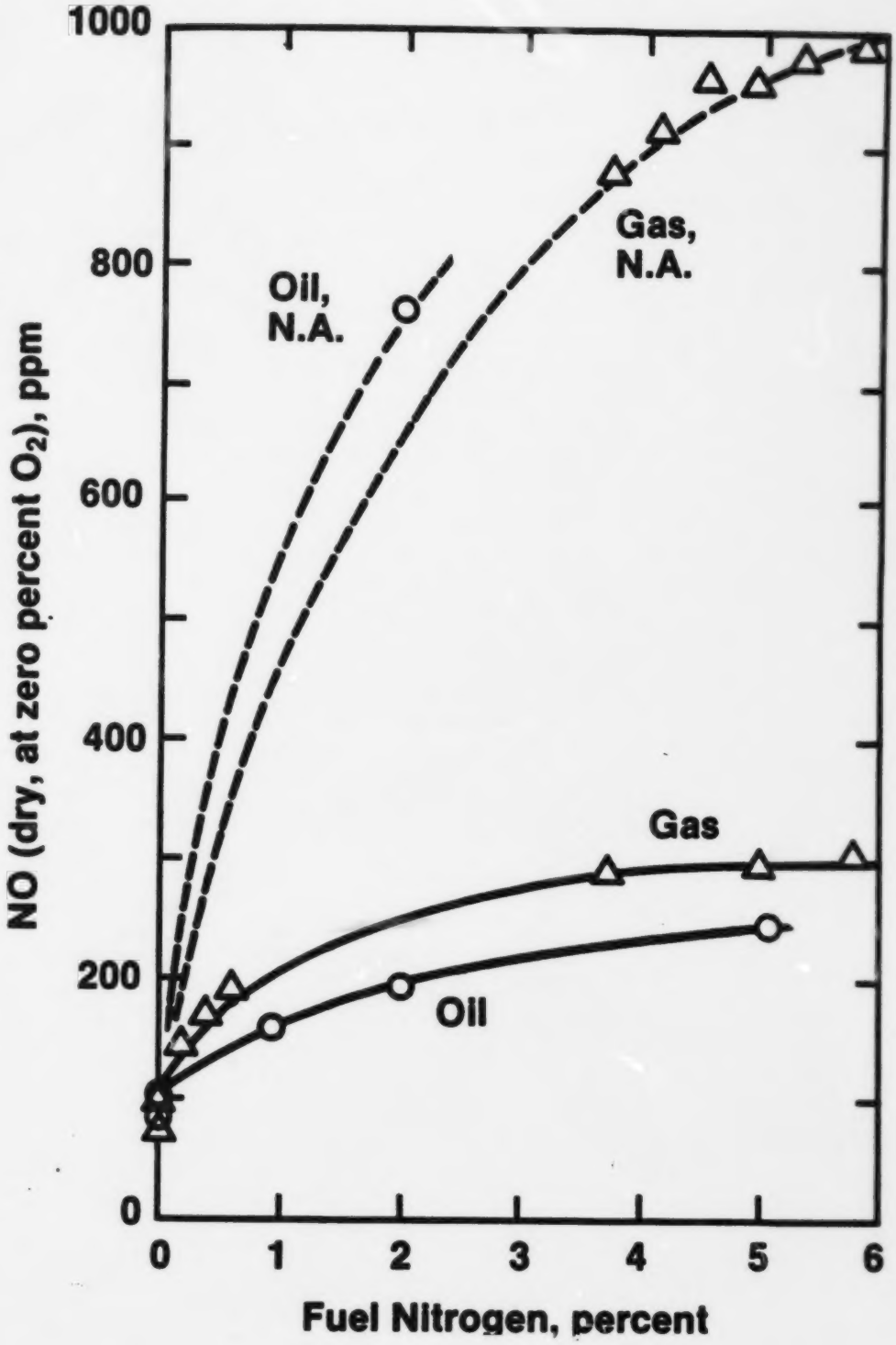
1000
800
600
400
200
0
NO (dry, at zero percent O_2), ppm
Oil, N.A.
Gas, N.A.
Gas
Oil
0
1
2
3
4
5
6
Fuel Nitrogen, percent

FIGURE 6